Final Technical Report

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"LINGERING EFFECTS OF NONLINEAR STRONG GROUND MOTION"

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Program Element II. Earthquake Physics and Effects

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LINGERING EFFECTS OF NONLINEAR STRONG GROUND MOTION

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Technical Abstract

Seismologists and engineers often make very different assumptions about wave propagation during strong ground motion. Seismologists typically assume that wave propagation is linear, such that commonly assumed principles, such as superposition, apply. Engineers, on the other hand, typically assume that wave propagation during strong ground motion is nonlinear, at least in the near-surface of soil sites, and results in a reduction of large amplitude ground motion during strong shaking. Our research will be important to both groups. It will be important to engineers because it has the potential to provide a measure of ground truth to the assumption of nonlinearity during strong ground motion. Moreover, by constraining the factors that control nonlinearity in strong ground motion, it should be possible to improve modelling of nonlinearity. Our research will be important to seismologists because if nonlinear effects are ignored, then source models derived from strong motion data, particularly for large earthquakes, may be inaccurate and biased.

Under this proposal we examined evidence for nonlinearity in strong ground motion in the 1984 Morgan Hill and 1989 Loma Prieta, California earthquakes, demonstrating the feasibility of using weak motion measurements to detect time varying characteristics of the Earth's crust caused by nonlinear mainshock strong ground motion using repeating microearthquakes. Following both of these earthquakes, we found a change in seismic velocity that is strongest just after the mainshock, always of the same sign (a decrease), and recovers linearly with the logarithm of time after the mainshock. A similar drop in velocity followed by logarithmic recovery is found in laboratory tests in which samples are subjected to large oscillatory strains. This correspondence, together with the fact that strains in the seismic near field are well into the nonlinear regime, leads us to conclude that the velocity changes we observe are a lingering effect of nonlinear mainshock strong ground motion. Thus, this approach provides a new tool to explore the circumstances under which nonlinearity occurs.

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Non-Technical Abstract

The damaging strong shaking in earthquakes is strongly influenced by "nonlinearity" in wave propagation. Nonlinearity, in this context, means that the strength of shaking is not as great as would otherwise be predicted, which is important information for coping with earthquake risk. Under this grant we have developed a new way to detect such nonlinearity, which uses the signals from small earthquakes. We find that nonlinearity is widespread and that its occurrence is most directly related to the strength of shaking, i.e., the stronger the shaking, the more important nonlinearity is.

Introduction

The effect of nonlinearity on strong ground motion is of fundamental importance to earthquake engineers but ignored by most earthquake seismologists. A great deal of work has been carried out on geotechnical aspects of nonlinear strong ground motion, but although seismologists have found evidence for nonlinear strong ground motion, its interpretation is subject to some ambiguity. Laboratory experiments suggest that at conditions in the shallow crust, nonlinearity should occur for strains exceeding about 10^{-6} (e.g., *Ten Cate et al.* [2000]). Typical earthquake stress drops imply strains of $\sim 10^{-4}$, suggesting that nonlinearity ought to be widespread in the near field of large earthquakes, at least near the Earth's surface

We have used repeating earthquake sequences on the Calaveras and San Andreas Faults in central California to document variations in the velocity of wave propagation in the Earth's crust that were caused by the 1984 M_w 6.2 Morgan Hill and 1989 M_w 6.9 Loma Prieta earthquakes [*Rubinstein and Beroza,* 2004; *Schaff and Beroza*, 2004]. By cross correlating waveforms we can reliably measure changes in the arrival time of seismic waves as small as several milliseconds from NCSN data. Figure 1 shows an example of such a measurement for the same set of repeating earthquakes recorded at two stations: one that shows significant changes and one that does not.

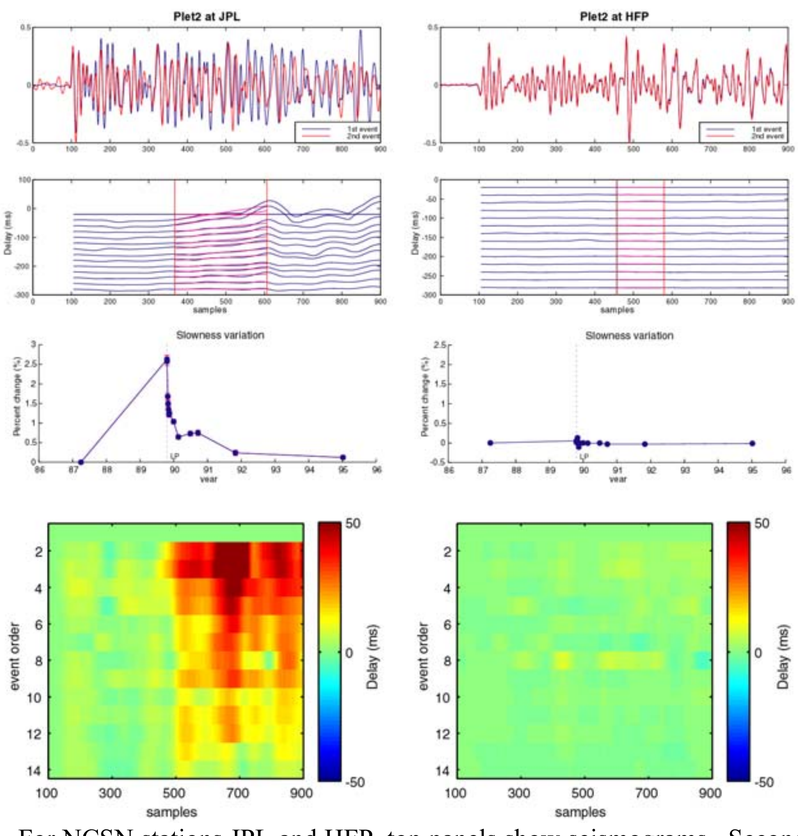

Figure 2. For NCSN stations JPL and HFP, top panels show seismograms. Second panels show results of running-window cross correlation for event pairs. Delays of the second seismogram relative to the first are manifest as upward trends. By fitting a slope to these delays, the signal can be interpreted as a percentage change in the path averaged slowness, shown in the third panel as a function of calendar time. Note large slowness increase at JPL following the Loma Prieta earthquake. Final panels show delays as the second panel, but in a format that is easier to view as part of a map display.

Spatial Variation of the Velocity Changes

Most stations near the Loma Prieta rupture zone have strong and similar time behavior. The anomaly is clearly the largest at stations JEC, JBZ, JTG, JPL, HPR, and HCB, which are located very near the mainshock rupture zone. For each of these stations there is a large delay in the arrival times of seismic waves after the Loma Prieta mainshock compared with the arrival times of the same seismic waves before the mainshock. The coherence of these waveforms approaches 100%, indicating that the change reflects a decrease in the wave propagation velocity of the Earth's crust caused by the Loma Prieta mainshock. Note that the sign of the signals in these cases, and to a lesser extent at the other stations as well, is uniformly positive (warm colors) - meaning the arrival times of seismic waves are in all cases delayed and never advanced - following the mainshock. Other stations at similar distances such as JAL, JST, and HGW show a much more subtle change. Similar results, though generally less dramatic, are obtained following the 1984 Morgan Hill earthquake.

Changes in arrival times can be seen at different times within the seismograms in the delay plots, but the changes are by far the most dramatic in the early *S*-wave coda. These waves are scattered from points in close proximity to a narrow scattering volume containing the hypocenter and the station. Most of the signal accumulates in the shallowest parts of the Earth's crust near the station for several reasons. Previous studies of the early seismic coda based on a comparison of borehole and surface recordings indicate that the coda is primarily generated by scattering in the vicinity of the station rather than more uniform, volume scattering throughout the earth's crust [*Blakeslee and Malin*, 1991; *Abercrombie,* 1997]. Moreover, *Dodge and Beroza* [1997] found from array analysis of several clusters of precisely relocated seismicity that the early coda for NCSN stations in this region is likely to be generated near the site. Finally, at stations where the effect is strongest, it appears as a linear "stretching" of the seismogram with time into the early *S*-wave coda. This is consistent with the accumulation of delay proportional to the time spent reverberating near the station.

The observed velocity change is quite large. For several stations it exceeds 50 milliseconds, (5 samples). The high degree of waveform similarity between these events is consistent with a measurement uncertainty of a fraction of a sample, indicating that the signal-to-noise ratio of the measurements for the stations at which the effect is most strongly manifest is well over ten. Another important aspect of the velocity change worth commenting on is that it is not permanent, but subsides with time.

Temporal Variation of Velocity Changes

The slowness increase (velocity decrease) is largest just after the mainshock and decays with time. The temporal behavior of this dependence is illustrated more clearly in figure 2, which shows the variation of the slowness change as a function of time as measured by several repeating earthquake sequences after both the Morgan Hill and Loma Prieta earthquakes. In each case following each earthquake, the variation of the amplitude of the anomaly with time can be approximated as a straight line if the amplitude of the slowness change is plotted against the *logarithm* of the time elapsed since the mainshock. We refer to such temporal behavior as logarithmic decay.

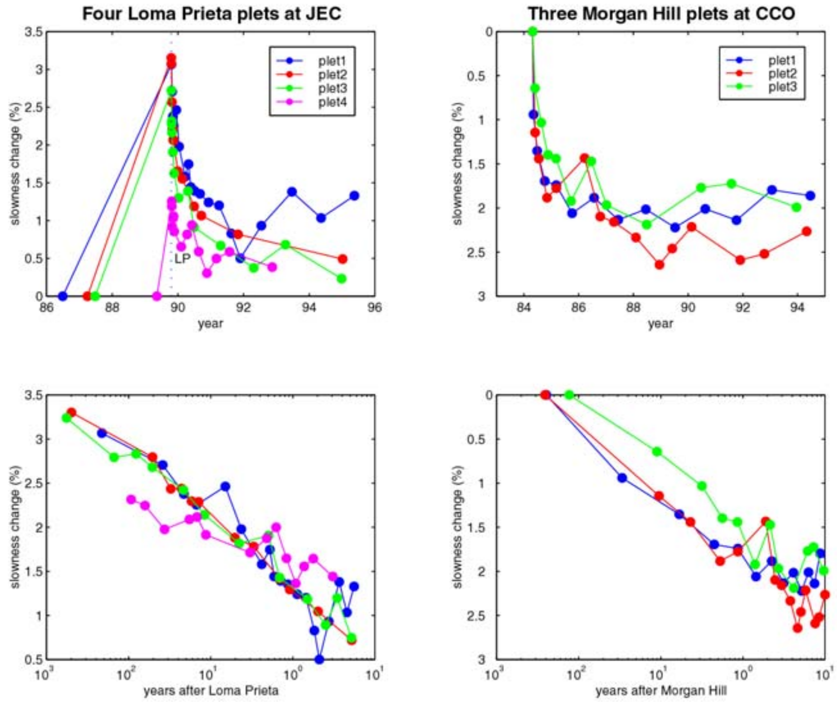

Figure 2. Estimated slowness change as a function of time following the Loma Prieta (left) and Morgan Hill (right) earthquakes as observed at two NCSN stations. Format is the same as in the third panel of figure 1. Results for the seven independent repeating earthquake sequences (plets) are similar. Lower panels show that the effect is linear in log-time after the two mainshocks. Note that for the case of the Loma Prieta mainshock zero change is defined as the pre-mainshock state, whereas, for the Morgan Hill earthquake it is the immediate post-mainshock state. We use this definition because the Morgan Hill earthquake occurred shortly after CALNET switched to digital recording and pre-1984 digitized waveforms for the Morgan Hill earthquake are not readily available.

A Signature of Nonlinearity

Ten Cate et al. [2000] carried out experiments on a range of materials under ambient laboratory conditions. They found that subjecting a wide variety of materials to oscillatory strains as small as 10^{-6} resulted in damage to the sample and a decrease of seismic velocity. This decrease in velocity diminished with time, logarithmically, once the large strains were removed. *Ten Cate et al.* [2000] also found that the amplitude of the velocity decrease scales with the level of strain that led to the nonlinearity, i.e. the larger the strain, the larger the velocity drop. All of their laboratory results are consistent with our observations following the two mainshocks. In both the laboratory and in the Earth: (1) strains in the near field of large earthquakes are several orders of magnitude higher than the strains at which nonlinearity in the laboratory first occurs, (2) where the velocity changes, it decreases when the large strains occur, (3) the recovery of velocity is logarithmic with time, and (4) the change in seismic velocity is largest where the strains are largest. This correspondence seems too great to be a coincidence, and we conclude that the laboratory samples and the earth's shallow crust are undergoing a similar process during which (perhaps recoverable) damage to the material is done during large dynamic strains.

Correlation of Nonlinearity with Ground Motion Amplitude

Figure 3 shows the relative delay of the initial *S* wave arrival at NCSN stations following Loma Prieta with four predictors. The first panel shows a correlation with distance to the fault. This is expected if the effect depends on the level of strong ground motion, but could also occur if the effect were due to the static stress change induced by the mainshock. The second panel shows the *S* delay vs. the change in the mean normal stress. If the delays were due to stress-mediated opening and closing of cracks [*Nur*, 1971], then regions where the sign of the velocity changes should correlate with whether the change in the sign of the mean normal stress. There is no such dependence since the change in velocity is always a decrease, so this mechanism cannot explain our observations. The final panels show the correlation with peak velocity and acceleration. The correlation is stronger with acceleration, though we had to interpolate these quantities to the locations of the NCSN stations because weak and strong motion instruments are not co-located. Nevertheless, the data are consistent with mainshock nonlinearity as the explanation of the observed velocity changes.

We find that the strength of strong ground motion correlates well with the observed *S*-delays. The PGA and PGV values in figure 3 are obtained from ShakeMaps [*Wald et al*., 1999; *Boatwright et al.*, 2004]. PGA and PGV measurements are interpolated. After examining the relation between the *S* delay and strong ground motion, it appears that there is a threshold, above which large delays start accumulating, of ~40 cm/s for velocity and ~30 percent of gravity for acceleration. Although ShakeMaps do take rock type and topography into account, our simple interpolation scheme does not, such that site effects specific to other locations may contaminate our interpolated ground motion values.

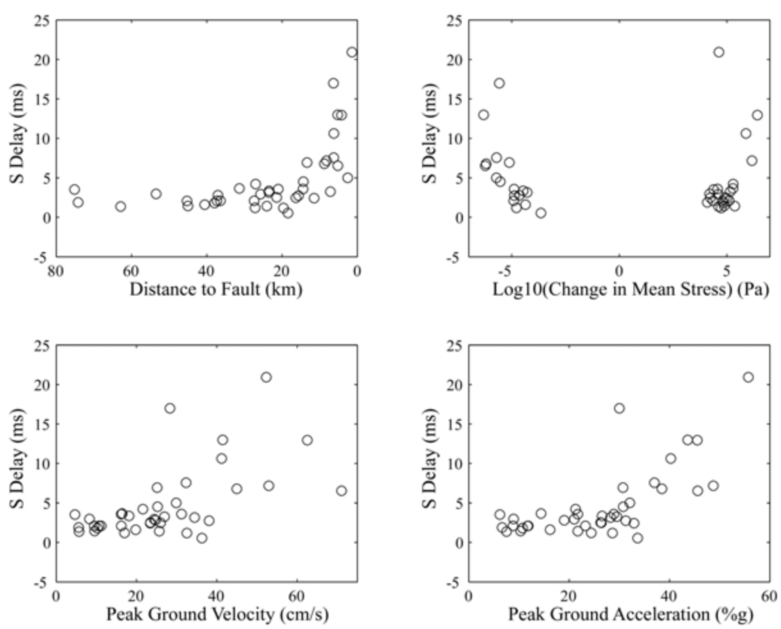

Figure 3. (upper left) Loma Prieta induced *S* delay vs. distance to the vertical projection of the upper limit of the rupture. (upper right) Delay vs. logarithm of the change in mean normal stress at the recording station. (lower right) Delay vs. peak ground velocity. (lower right) Delay vs. inferred peak ground acceleration.

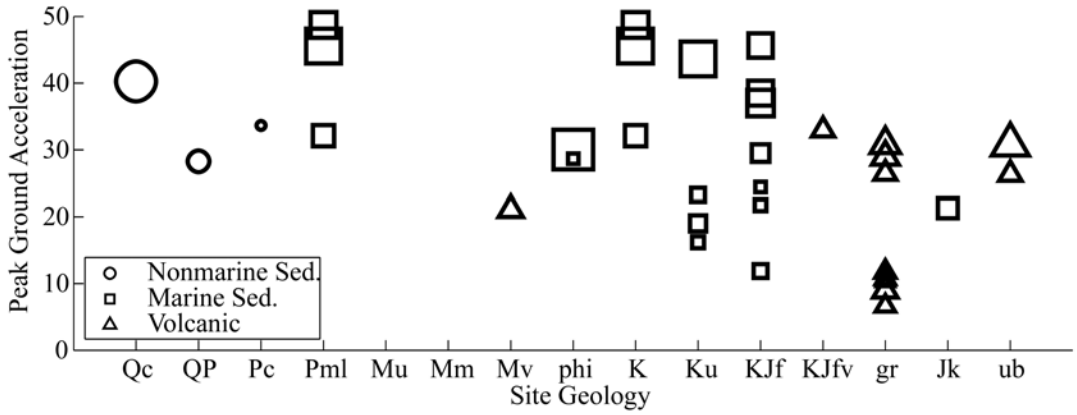

Figure 4. Correlation of PGA with site geology and the *S*-wave delay shown with the symbol size. Magnitude of delays correlates weakly with the surface geology. Stations on sedimentary units show large delays and the largest of them are observed at the sites located on the youngest rock. This suggests that younger sedimentary rocks may be more susceptible to nonlinearity than older sedimentary rocks. There are a number of cases where different geologic units have similar velocity change, suggesting that the level of strong ground shaking, rather than the susceptibility of a geologic unit to damage, is the dominant factor.

Correlation with Measurements of Coda Amplification

Figure 5 is similar to figure 4, but with a measure of the amplification of the coda found by *Phillips and Aki* [1986]. The correlation of the velocity change effect with sites that show strong site amplification in the seismic coda of microearthquakes, which is derived from the same NCSN stations that we analyzed, is stronger than for the site geology. Site geology, coda amplification, and the amplitude of strong ground motion are all strongly correlated parameters, however, our limited dataset suggests that the level of strong ground motion, rather than site conditions, is the strongest factor in predicting ground motion nonlinearity.

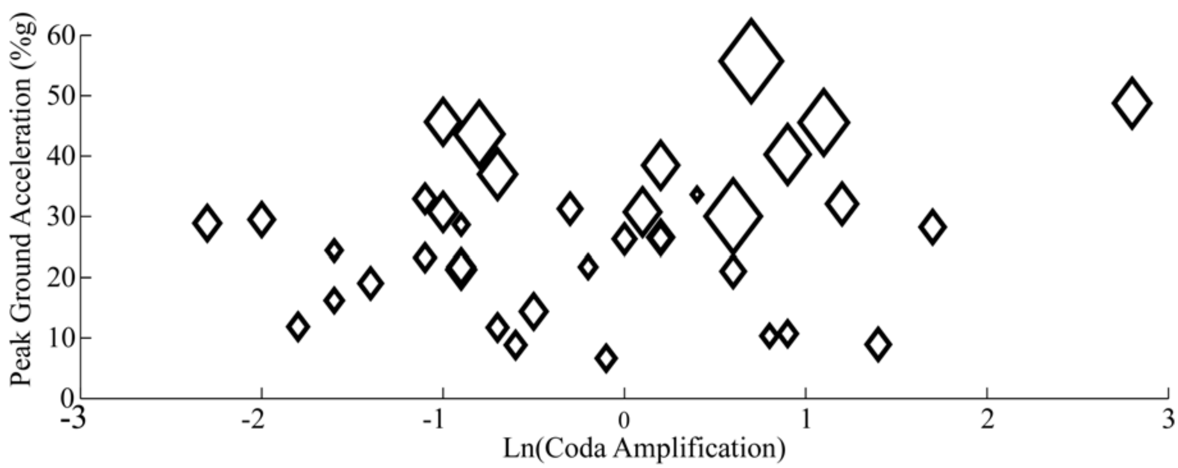

Figure 5. Correlation of PGA with coda amplification factor as determined by *Phillips and Aki* [1986] with magnitude of the observed *S* delays shown with symbol size. Intensity of strong shaking is strongly correlated with the magnitude of the delays. Nearly every station that undergoes high peak acceleration (above 30% g) has larger delays associated with it than stations that experience weaker ground motion.

As stated previously, seismologists and engineers take a different view of the importance of nonlinearity in strong ground motion. We believe that we have uncovered convincing evidence that nonlinearity, at least at some level, may be widespread and that it may occur even at rock sites. Even if we accept this notion, the strength of nonlinearity during strong ground motion is something we might be able to bound, but which is much more difficult measure directly. Thus our research may only provide a partial assessment of the importance of nonlinearity in strong ground motion. Nevertheless, the importance of these phenomena to all aspects of strong ground motion suggests that we need to learn what we can from the data we have.

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Publications resulting from this grant include:

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